

SUPERPLASTIC FORMING OF AL-LI ALLOYS FOR LIGHTWEIGHT, LOW-COST STRUCTURES

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ABSTRACT

Superplastic forming of advanced aluminum alloys is being evaluated as an approach for fabricating low-cost, light-weight cryogenic propellant tanks. Built-up structure concepts (with inherent reduced scrap rate) are under investigation to offset the additional raw material expenses incurred by using aluminum-lithium alloys. This approach to fabrication offers the potential for significant improvements in both structural efficiency and overall manufacturing costs. Superplasticity is the ability of specially processed material to sustain very large forming strains without failure at elevated temperatures under controlled deformation conditions. It has been demonstrated that superplastic forming technology can be used to fabricate complex structural components in a single operation and increase structural efficiency by as much as 60 percent compared to conventional configurations in skin-stiffened structures. Details involved in the application of this technology to commercial grade superplastic aluminum-lithium material are presented. Included are identification of optimum forming parameters, development of forming procedures and assessment of final part quality in terms of cavitation volume and thickness variation.

INTRODUCTION

Conventional methods for fabricating Al alloy sheet product, such as brake forming or roll forming, usually involve multiple-step cold forming and intermediate heat treating operations. The forming loads required exceed the material yield stress and for high strength alloys the maximum allowable elongation is typically less than 10 percent [1]. This limited ductility restricts the capabilities of conventional forming to relatively simple structural shapes for high strength Al alloys. In comparison, by utilizing the capabilities of superplastic materials, parts can be designed with up to 200 pct. thickness strain and formed at relatively low stresses. This creates versatility in the shapes that can be formed and permits the fabrication of components with more complex geometries [1].

There are many instances in which the increased formability afforded by the superplastic forming (SPF) process has been employed where part complexity has dictated that conventional forming techniques are impractical [2]. Fabrication of sheet structures using SPF technology has permitted the replacement of components consisting of multiple parts, with a single, or greatly reduced number of parts [1]. The technology has also provided additional production flexibility through the capability of fast turnaround for redesigned parts [2]. Overall savings in manufacturing costs have been realized as a consequence of reductions in part/fastener inventories, assembly operations and material scrap rate [3]. The level of automation allowed by the process has reduced the reject rate through decreased reliance on operator skill [4]. The dimensional accuracy of individual components and the repeatability between components has also caused significant reductions in the cost of secondary forming and straightening operations [2].

SPF technology is also a viable alternative where multiple-step forming has proved to be prohibitively expensive [5]. Such instances typically involve production of a restricted number of complex components. Cost savings have been realized through the fabrication of parts in a single forming operation and the elimination of multiple pressing and heat treatment operations [5]. As a result of the requirement for sets of precision tooling with moving and mated die components, the non-recurring tooling costs are high in conventional forming operations [6]. In order to be cost effective, the production volume is necessarily large to offset these expenses. By comparison, the cost of SPF tooling is much lower, as a result of the requirement for one simple cavity die [1]. However, the dedicated control equipment necessary and the relatively low throughput of forming machines combine to inflate costs [7]. Therefore, the cost balance for SPF favors low to moderate volume, where the lower tooling costs are offset by the higher costs of longer production cycle times [7]. The specific volume for which SPF is cost effective is dependent on component complexity and the number of conventional forming steps eliminated [5].

It is clear that for cost effective application of SPF technology there are many factors to be considered which require an understanding of the flexibilities and limitations of the basic process. Therefore, it is the goal of this paper to introduce engineers outside the aerospace industry to the advantages of SPF as an alternate forming technique. The intention is to familiarize readers with the process itself and also illustrate in cursory detail how it may be applied.

BACKGROUND

Superplasticity is used to describe the exceptional elevated temperature ductility exhibited by certain materials when deformed under specific conditions. During uniaxial deformation, tensile elongations of 500-1000% are typical, and at flow stress levels well below ambient temperature yield stress. The primary microstructural requirement is an equiaxed grain structure of the order of 10 μm , which is stable at the SPF temperature of the material [8]. The fine grain size can exist in the material prior to SPF or be developed during the SPF process. In both cases, the refined grain structure is promoted by controlled thermomechanical treatments during the processing leading to sheet product. The microstructural stability required for superplastic deformation is usually imparted by a uniform dispersion of fine particles within the material which inhibit grain coarsening [8].

Superplastic behavior is extremely temperature and strain rate sensitive which dictates that there are considerable constraints on the deformation conditions for achieving large elongations. Typically, temperatures in the range of 70-90 percent of the alloy melting point and controlled strain rates in the range of 10^{-4} to 10^{-2} sec^{-1} are required [8]. Within this 'window', the resistance to localized necking is high which results in uniform thinning of the material and large strains to failure. The predominant mode of deformation during superplastic flow is grain boundary sliding which can create microvoids at grain boundary triple points at high strain levels [9]. The formation of these voids, known collectively as cavitation, can be suppressed by the application of a hydrostatic stress during, or following, deformation.

SPF OF STRUCTURAL COMPONENTS

During SPF of actual components, the inherent low forming stresses allow the use of gas pressure as the deformation medium, rather than hydraulic or mechanical driven tools [7]. The most common form of SPF involves biaxial forming of sheet material into female dies containing male inserts in a variety of configurations. A schematic cross-section of the facility constructed at NASA-Langley Research Center (LaRC) for SPF of structural components is presented in Figure 1. The apparatus, which constitutes a pressure vessel, consists of upper and lower steel platens with a gasket area designed into the periphery. The assembly is mounted in a hydraulic press, such that when a compressive load is applied a gas-tight seal is created along the perimeter of the superplastic sheet. The SPF tooling recessed into the platens is composed of a female die box within which removable male inserts are located. The appropriate forming temperature is achieved via resistance heaters located within ceramic blocks attached to the outer surface of the platens. The entire assembly is insulated against heat loss and the tooling is coated with a release agent to facilitate part removal following forming. The forming stress required for SPF is generated by argon gas pressure which is introduced through a manifold using a microprocessor-controlled regulator. The gas is admitted at the rate specified for forming at the constant strain rate selected from prior parametric evaluation of the uniaxial superplastic behavior of the material.

Pressure-time profiles are determined primarily through geometrical consideration of the superplastic sheet at the various stages of forming in conjunction with material flow characteristics [10]. The initial stage of deformation constitutes bulge formation, with the highest rate of sheet thinning occurring at the tip of the forming dome [6]. On die contact, thinning is inhibited by frictional effects and continued thinning during the intermediate stages is restricted to areas of the sheet not in contact with the die. The final stage of the process is when the deforming sheet conforms to the contours of the die [7]. Even though forming profiles are specific to component geometry, the cycle time is primarily a function of the maximum strain and is therefore independent of the size of the sheet being formed. During SPF of complex shapes or multiple parts, the fastest forming element of the overall design can be formed at the optimum strain rate with the remaining elements forming at a lower local strain rate [2].

The rate of gas pressurization is designed to maintain the strain rate for optimum superplastic response as the thickness and geometry of the deforming sheet changes. The thickness distribution in finished parts can be controlled through judicious selection of tool geometry and careful control of process parameters. The thickness of the final component tends to be at a minimum in those locations corresponding to last points of contact of the deforming sheet with the SPF die. Thus, the width-to-depth (aspect) ratio of the female cavity governs the total thickness strain and choice of corner radii for the male insert controls the extent of localized thinning [6]. The type of release agent employed for part removal determines the level of friction between the deforming sheet and the die. This controls the amount of sheet thinning following die contact and ultimately the thickness gradient across the part [6].

Some generic examples of the application of SPF technology to the manufacture of aerospace components are illustrated in Table 1 [2]. The most appropriate applications for this technology have proved to be deep shapes with compound curvature or corrugated panels with complex details [1]. SPF has allowed the fabrication of monolithic structures that are not only more cost effective, but also often more structurally efficient. It is of particular significance to this study that the technology has been extended to include the fabrication of large, integrally stiffened, sheet structures [3]. In previous work at NASA-LaRC on SPF of titanium alloys, it has been shown that the compressive load-bearing capacity of skin-stiffened panels can be increased by as much as 60 percent by using SPF stiffeners with unique web configurations [11,12].

A characteristic of SPF components is the excellent repeatability of part dimensions which yields tolerances equivalent to machining [2]. The structural performance of components tends to benefit from the low variability in shape and thickness from one component to another. From the perspective of structural efficiency, it is desirable to minimize sheet thickness while controlling the thickness variations inherent in SPF components. The capability of the SPF process for tighter thickness tolerances compared

to conventional forming techniques allows designs to incorporate thinner gages leading to more efficient structures [1]. An additional advantage, associated with using single surface tooling, is that sheets of different starting thicknesses may be formed to identical dimensions. This creates production flexibility for satisfying specific structural strength, weight and cost parameters [5].

A major emphasis in the development of the SPF process has been concerned with minimizing the volume of cavitation in finished components [4]. Usually, cavitation is effectively suppressed during SPF by the application of a superimposed back pressure, but hot isostatic pressing (HIP'ing) following SPF has also been employed [4]. The level of back pressure required to attain a total void volume of less than 1 percent is typically of the order of the uniaxial flow stress of the material being formed [13]. Prior investigations at NASA-LaRC have demonstrated that cavitation can also be reduced by using a post-forming pressure cycle. This consisted of a specified holding time at the maximum pressure of the equipment at the conclusion of forming [14].

ALUMINUM-LITHIUM ALLOYS

A large development in the aerospace industry at present is concerned with the potential applications of aluminum-lithium (Al-Li) based alloys. The emergence of these alloys, which typically possess 10-20 percent higher specific properties than existing Al alloys, heralds the expansion of SPF technology into primary structure applications [4]. Success with conventional fabrication of sheet product has been limited because Al-Li alloys tend to develop surface shear steps and have an increased propensity for cracking [15]. This has been attributed to prominent microstructural directionality, which also results in mechanical property anisotropy following fabrication. The culmination of this effect is that forming operations must consider the rolling direction in the starting sheet. As a consequence, the scrap rate is necessarily increased to compensate for the directionality in material behavior.

The limitation in formability of Al-Li alloys, typically to radii greater than twice the thickness, has also precluded the fabrication of intricate structural shapes by conventional means [15]. However, since Al-Li alloys can be thermomechanically processed into superplastic sheet, SPF offers the potential to produce complex structural shapes from these materials. Much of the work concerning superplastic versions of these alloys has tended to involve laboratory-scale material, such that the existing database on commercially available material is limited at present [16,17]. The microstructure of superplastic Al-Li alloys is unrecrystallized in the thermomechanically processed condition and relies on conversion into a refined grain structure with the accumulation of strain during SPF [18]. Historically, one of the inconsistencies associated with superplastic materials has been the inability to meet the microstructural prerequisites during scale-up to commercial-sized ingots. Material characteristics have tended to vary from lot to lot, such that it has proved necessary to check the superplastic properties of each heat. Published literature concerned with the manufacture of superplastic Al-Li alloys and the practical aspects of SPF has also been limited because of the commercial sensitivity of the information [19].

The commercial Al-Li alloys available at present are 2090 produced by ALCOA, 8090 produced by British Alcan, and X2095 (formerly Weldalite™049), produced by Reynolds. Information on the SPF behavior of these alloys is available from the vendors, but much less data exist on the effect of SPF on mechanical properties [18]. Most data have been generated from uniaxially deformed sheet rather than from biaxially formed material. The typical post-SPF properties of these alloys in the T6 (peak aged) condition is compared with 2219 in the T8 (cold stretched + peak aged) condition in Table 2. It should be noted that as with many superplastic materials there is reduction in the strength of Al-Li alloys in the post-SPF condition. However, for the purposes of this investigation, it can be seen that the mechanical properties of post-SPF materials are comparable with those of the current 2219 cryogenic tank material. It should be noted that a yield strength of 87 ksi, with an elongation of 6 percent, for the X2095 material is impressive relative to other Al alloys in any condition.

SPF OF AL-LI COMPONENTS FOR CRYOGENIC TANKS

One activity at NASA-LaRC is focussed on the use of built-up sheet metal structures in the manufacture of cryogenic propellant tanks. The program advocates SPF and Resistance Spot Welding (RSW) of Al-Li alloys for low-cost fabrication of skin-stiffened structures with reduced structural weight. The Space Shuttle External Tank is currently fabricated from alloy 2219 plate with up to 2" starting thickness. The material is machined into integrally T-stiffened panels and formed to the outer radius of the tank prior to assembly. As indicated in Figure 2, panel fabrication by this route results in a scrap rate of approximately 90 percent. It is envisioned that the built-up structure approach using SPF technology will reduce the scrap rate to approximately 15 percent. The decrease in the material buy-to-fly ratio will allow the use of the more expensive Al-Li alloys and exploitation of improved mechanical properties.

The stiffener configurations considered in this investigation are illustrated schematically in Figure 3 and are compared with the existing integrally T-stiffened design. Since thin sheet structures are generally considered to be stiffness critical from the design standpoint [18], the superplastic versions of the Al-Li alloys 8090, 2090 and X2095, which possess high specific modulus, were considered prime candidates for this application. In order to assess the superplastic behavior of these materials, parametric studies were conducted over a range of temperatures and constant strain rates using uniaxial tension tests. The data presented in Table 3 are a summation of the optimum parameters identified in this investigation for SPF of the three alloys.

For SPF of the stiffener components, gas pressurization cycles were established based on this uniaxial tensile data and consideration of the die geometry. The plain hat configuration had the simplest geometry and was used for the purposes of the analysis summarized in Figure 4 for 8090. The forming cycle was divided into the three distinct stages outlined and the geometry of the unsupported areas of the deforming sheet was approximated by either a sphere or a combination of a sphere and a cylinder. For each stage, the pressure required was calculated via conventional shell theory using instantaneous sheet thickness, radius of curvature and flow stress [10]. The corresponding forming times required were estimated by dividing the incremental true linear strain by the strain rate selected. Interrupted forming cycles were used to determine the extent of forming and revise the predicted cycle where necessary. Using this empirical approach, the durations of the three stages of forming were established and compiled to generate the complete forming profiles [14]. Modifications to the initial forming profile, die geometry and forming procedures were also made to improve final part quality and reduce total forming time. This permitted pressure-time profiles to be developed which maintained a constant rate of deformation corresponding to the strain rate for optimum superplastic formability.

Assessment of the level of back pressure and post-forming pressure required to suppress cavitation was conducted prior to establishing the pressure-time profiles for the forming of actual parts. The results are summarized in Figure 5 for 8090 and X2095, which shows the volume of cavitation in simple 'loaf pans' as a function of the applied hydrostatic pressure normalized with respect to flow stress. As mentioned earlier, the level of hydrostatic pressure required is usually of the order of the flow stress [13]. In order to reduce the total volume of cavitation to less than 1 percent, it is apparent that a pressure somewhat less than the flow stress can be employed to minimize cavitation, particularly if a post-forming pressure cycle is employed. This has significant implications for SPF in facilities with limited pressure capability because it allows for higher differential forming pressures. In this investigation, the maximum inert gas forming pressure, combined with the superimposed back pressure to suppress cavitation could not exceed the 500 psi limitation of the SPF facility. An example of a final forming profile, including superimposed back pressure and a post-forming pressure cycle, is shown in Figure 6 for SPF of 8090 material.

Examination of the initial parts formed revealed localized thinning adjacent to the intersection of the cap with the web. This 'eyebrow' effect was considered undesirable from the perspective of structural performance [11]. The corner radius, which had not been specified during die manufacture, was increased to discourage adjacent thinning, but the effect persisted in subsequent parts [14]. It was concluded upon further examination that deformation of the material in the cap area had apparently continued on contact

with the die. Based on prior experience with SPF of titanium alloys, the tooling had been coated with a boron nitride slurry which may be classified as a die lubricant. In an attempt to reduce localized thinning, the SPF cycle was repeated following replacement with a yttrium oxide slurry. Yttrium oxide is considered to be a release agent, rather than a lubricant, since experience has shown that much greater friction is created between the deforming sheet and the die [6]. As a result of this procedure modification, the eyebrow effect was eliminated and the final parts conformed closely to the dimensions of the tooling.

Subsequently, the SPF process was applied to the more complicated stiffener configurations and to the other two Al-Li alloys. The net result of this investigation was that demonstration components of each alloy in each configuration were successfully fabricated using SPF. Components were easily removed from the tooling and were formed with good dimensional conformity to the die. Figure 7 shows examples of the SPF plain web stiffener components fabricated from the three alloys assessed in this study. The parts have been heat treated to peak strength and only partially trimmed for demonstration purposes. Following further trimming these were resistance spot welded to skin material to produce buckling panels for evaluation of relative structural efficiency. Compression panel testing and assessment of the mechanical properties of the materials at ambient and cryogenic temperatures is the focus of current investigations.

SUMMARY

SPF has the potential to significantly reduce manufacturing costs in instances where the requirement is for low to moderate volume production. The technology readily lends itself to the fabrication of sheet metal components which are difficult or impossible to produce using conventional methods. The potential improvement in maintainability and reliability resulting from decreased part and fastener count is particularly attractive. As demonstrated in this investigation, the large forming strains permitted by SPF have resulted in the fabrication of skin-stiffened panels with complex configurations. It is anticipated that employing SPF and Al-Li alloys in the fabrication of built-up cryogenic tank structures will result in weight and cost savings. The reductions in systems costs, through lower density, and manufacturing costs, through lower scrap rate and reduced machining time, are expected to be appreciable. The use of Al-Li alloys is recognized as being restricted to applications where structural weight is critical. However, the cost saving benefits of using SPF technology outlined can be applicable to industries engaged in sheet metal forming operations.

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Table 1. Typical Aerospace Applications of SPF.

Application:	Examples:
Stability Designed Structures	Ribs Frames Beams Compression Struts
Complex Multi-Element Sheet Components	Panels Mounting Brackets Supports
Complex Envelopes (SPF/DB)	Ducting Tanks Vessels

Table 2. Al-Li Alloy Post-SPF Properties Compared with Al 2219.

Property:	2219-T87	8090-T6	2090-T6	X2095-T6
Density (lbs/in. ³)	0.102	0.092	0.094	0.098
Modulus ($\times 10^3$ ksi)	10.6	11.3	11.5	11.3
Tensile strength (ksi)	63	60	61	90
Yield strength (ksi)	52	45	47	87
Elongation (pct)	6	6	8	6

Table 3. Optimum SPF Parameters from Uniaxial Data.

Parameter:	8090	2090	X2095
Temperature (°F)	985	950	925
Strain Rate ($\times 10^{-4}$ s ⁻¹)	2.5	5.0	6.0
Failure Strain (pct)	510	775	810
Flow Stress (ksi)	0.4	0.6	0.8

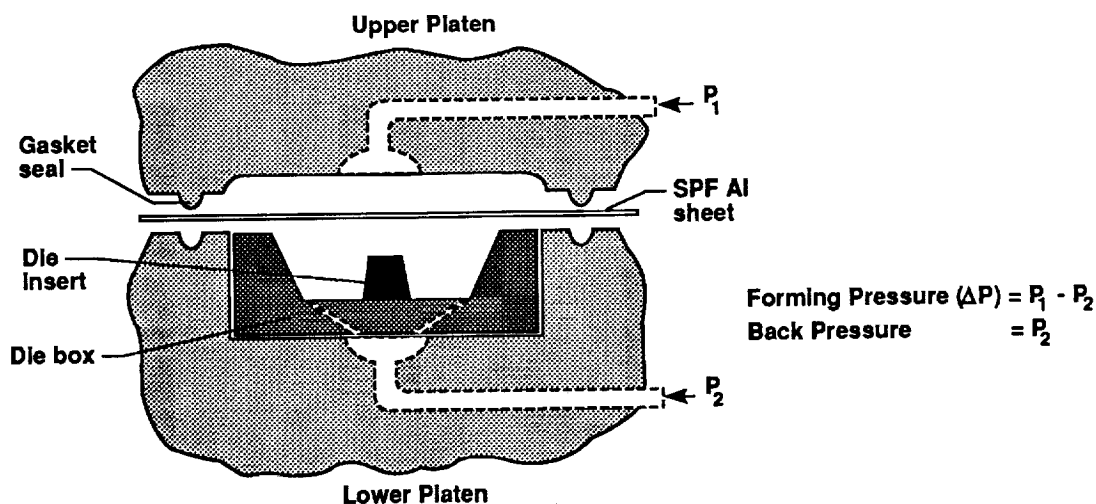


Figure 1. Schematic cut-away representation of the cross-section of the SPF facility used for fabricating structural components. The resistance-heated platen assembly is located within a hydraulic press.

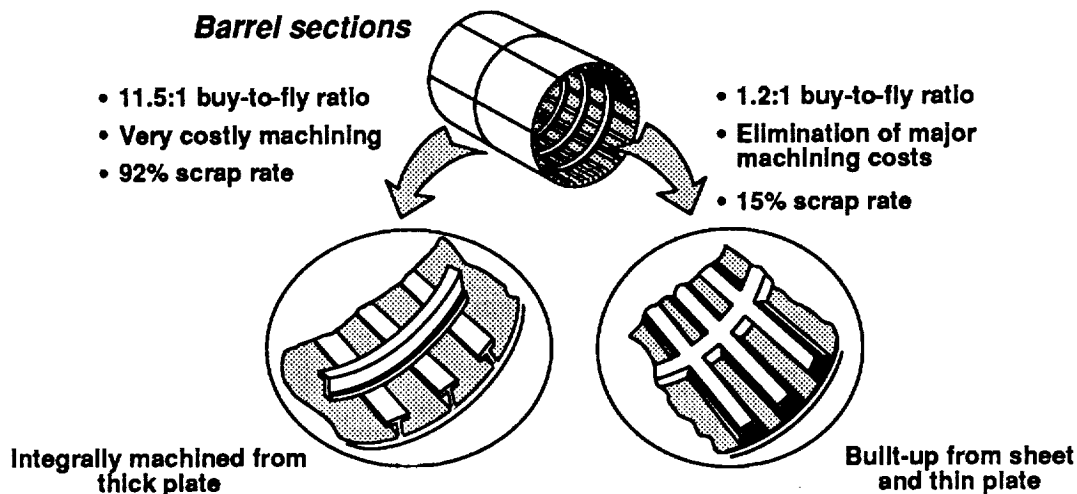


Figure 2. Factors highlighting the potential cost reductions associated with fabricating barrel sections for cryogenic propellant tanks using the built-up structure approach.

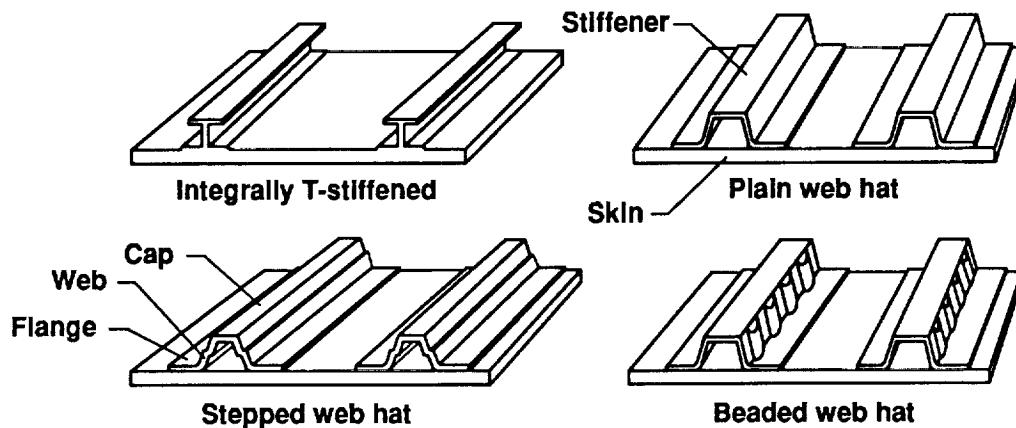


Figure 3. A comparison between the current T-stiffened design for the Space Shuttle External Tank and three SPF stiffener configurations.

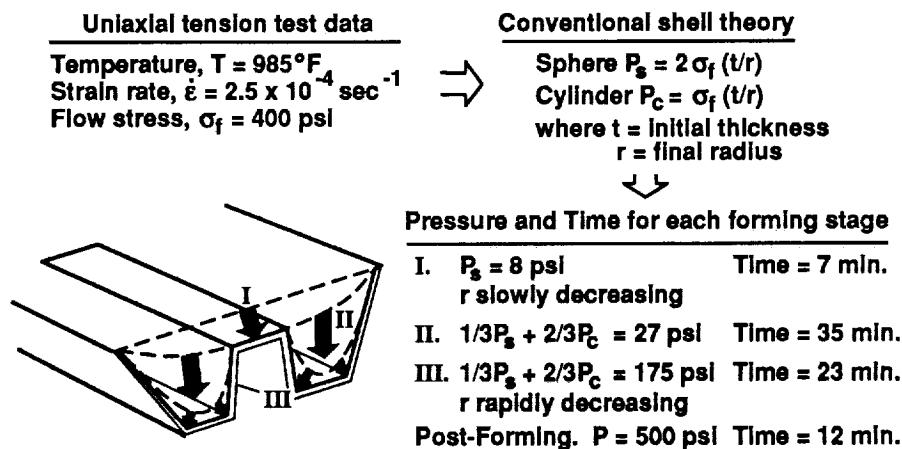


Figure 4. Summary of method used to establish gas pressurization cycle for SPF of 8090 stiffener (plain web configuration) at a constant forming rate.

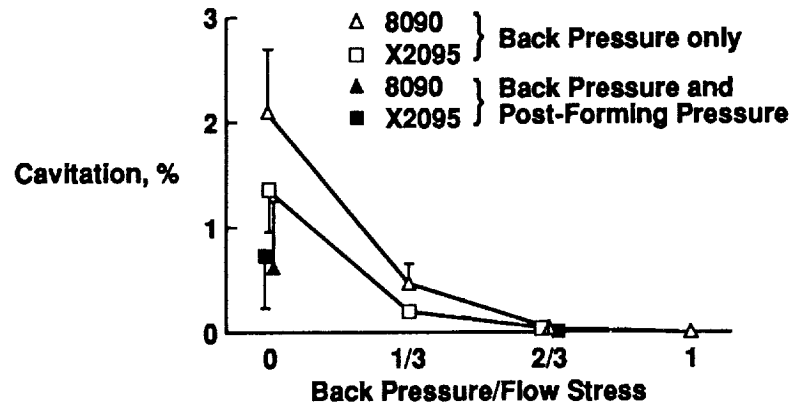


Figure 5. Effect of back pressure and post-forming pressure on cavitation during SPF of 8090 and X2095.

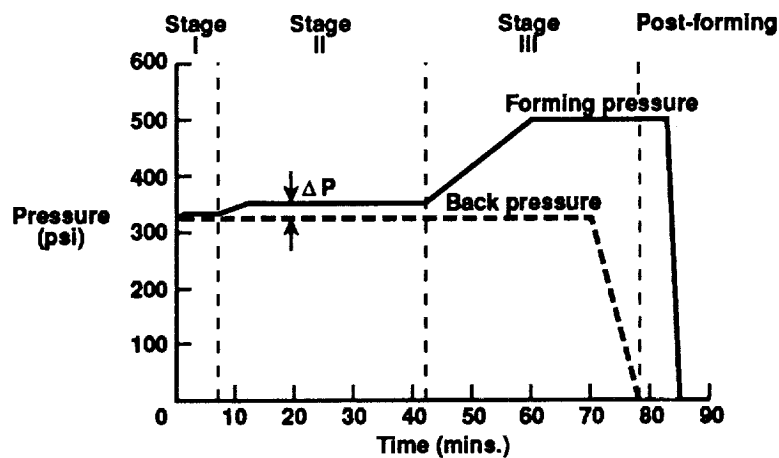


Figure 6. Pressure versus time profile for superplastic forming of 8090 at 985°F corresponding to a strain rate of $2.5 \times 10^{-4} \text{ sec}^{-1}$.



Figure 7. Partially trimmed SPF plain web stiffener components fabricated from 8090, 2090 and X2095 (Weldalite 049). The optimum parameters for forming and post-forming heat treatment are identified for each of the Al-Li alloys.